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Probabilistic design of water defense systems in The Netherlands

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Abstract

After the disaster in 1953, a statistical approach to the storm surge levels was chosen and an extrapolated storm surge level would be the basis for dike design. In recent decades, the development of reliability theory made it possible to assess the flooding risks taking into account the multiple failure mechanisms of a dike section and the length effect. It is pointed out that economic activity in the protected areas has grown considerably since the 1950s and that even more ambitious private and public investments, particularly in infrastructure, are planned. Moreover, the safety of a growing population is at stake. These considerations justify a fundamental reassessment of the acceptability of the flood risks. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Approximately half of the Netherlands lies below sea level and is protected against flooding by primary dikes and other water-retaining structures. Extensive systems of drainage channels and storage basins with associated water-retaining structures and pumping capacity ensure artificial management of surface and groundwater levels. In the middle ages, the dikes were designed at the highest known storm surge plus one metre additional freeboard. This practice had to be abandoned in the design of the Afsluitdijk, where no observations were available. The famous Prof. Lorentz predicted the increases in tidal level and to these observations of wind set-up at the Friesian coast was added. After the disaster in 1953 a statistical approach to the storm surge levels was chosen and an extrapolated storm surge level would be the basis for dike design [14]. It will be described how the Delta Committee optimised these safety levels that were expressed in terms of the return period of high water levels, which must be withstood by the primary dike system.

Flooding is a typical high-consequence low-probability event and can as such be compared with other technological matters in society. The Institute of Chemical Engineering [6] for instance published in 1985 a document on hazard and risk assessments in the process industries; HMSO's Department of Environment [3] investigated risks in shipping, the Dutch Aerospace Laboratory analysed safety around the airport Schiphol [8], and the Dutch Ministry of Housing, Land Use Planning and Environment [7] and the British HSE [5] produced guidelines for land-use planning relating to risks. Vrijling et al. [20] derived a framework for evaluation of risk, in general.

Since 1980 the development and application of reliability theory made it possible to assess the flooding risks, taking into account the multiple failure mechanisms of a structure. Dutch hydraulic engineers were among the first to apply this theory in the practical design of structures. Reliability models were first used during the design and the construction of storm surge barrier in the Eastern Scheldt in 1976 and later in the design of storm surge barrier in the Nieuwe Waterweg.

In the 1980s projects were started to apply the probabilistic methods to the design of dikes in general. The development of a complete approach to water defense systems took a considerable time. Recently, the approach was tested on four polders or dike rings. The probability of flooding of these polders was calculated and insight into the weak spots was gained. Some results will be presented below. It is expected that the results of the calculations will stimulate the political debate if the present safety level of the water defense system is still sufficient. This question should be posed because the economic activity in the protected areas has grown considerably since the 1960s. Moreover,

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ambitious private and public investments, particularly in infrastructure, are planned. The national economy has and will become more vulnerable to flooding. In addition, the safety of a growing number of inhabitants is at stake. In future, the environmental consequences of flooding and the potential effects on nature and cultural heritage will play a larger role in assessing the required scale of flood protection. The image of The Netherlands as a safe country to live, work, and invest is an important factor to consider. This may justify a fundamental reassessment of the acceptability of the flood risks and the development of a plan to improve the effectiveness of the water defense system in the course of the coming decades.

2. The approach to dike design since the Delta Committee

The present approach to the safe design of dikes is based on the findings of the Delta Committee that were published in 1960 [13]. In 1953 large parts of the south-western Delta of the Netherlands were flooded by an extreme storm surge. Apart from considerable economic losses, 1800 people lost their lives. The main cause of the failure during the storm of the 1st February 1953 was overtopping followed by the erosion and sliding of the inner slope of the dikes. Besides the development of the Delta-plan to shorten the coastline by closing the estuaries, the Delta Committee focused on the design of dikes. Two main improvements were proposed: (1) increase the design water level and consequently the crest height of the dike; (2) flatten the inner slope of the dike to 1:3. The new design water level was established in two steps. First, the observations of the previous hundred years were statistically analysed and extrapolated to levels never exceeded before. Secondly, an economic optimisation of the design water level was performed. On the one hand the damage that a flooding of Central Holland would cause was estimated (indicated by S in Fig. 1), and on the other the cost of increasing the height of the dikes was calculated (indicated by I). Because a higher and more expensive dike leads to a reduction of the probability of flooding P_f and therewith of the occurrence of damage an optimal design water level could be found ($P_{f\,opt}$). $P_{f\,opt}$ is the value for which the curve Q (which is the summation of the costs of investment I and the PV (present value) of the risk P_fS) takes its minimum (see Fig. 1).

The design water level for Central Holland was fixed at 5 m + NAP (Amsterdam Ordnance Datum) with a return period of 10,000 years (following from statistical analysis of historical data of water levels at the location of Hook of Holland). Because the flood damage in more rural areas than Central Holland would be less, shorter return periods of 4000 and 3000 years were chosen for these polders. Today, the Netherlands is divided into 53 polders each with a specified design return period or frequency. The Delta Committee knew that other failure mechanisms than overtopping and sliding could be dangerous; therefore additional design requirements were formulated in a classical way. A similar approach was used in breakwaters designs [15].

3. The probabilistic approach of flooding

Since 1980 the awareness grew that the probability of exceedance of the design water level, the design frequency or the reciprocal of the return period is not a good predictor of the probability of flooding. Normally, the dike crest exceeds the design water level by some measure, thus the probability of overtopping is smaller than the design frequency. But some parts of the dike may already be critically loaded before the design water level is reached. Waterlogging may lead to slide planes though the dike or piping may undermine the body of the dike, with sudden failure as a consequence. Another danger is that sluices and gates are not closed in time before the high water. In short, there are more failure mechanisms that can lead to flooding of the polder than overtopping (see Fig. 2). Moreover, the

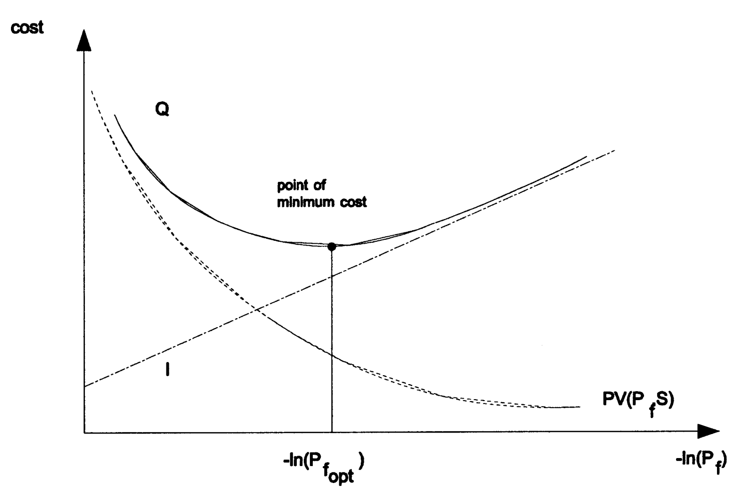

Fig. 1. The economically optical probability of failure of a structure.

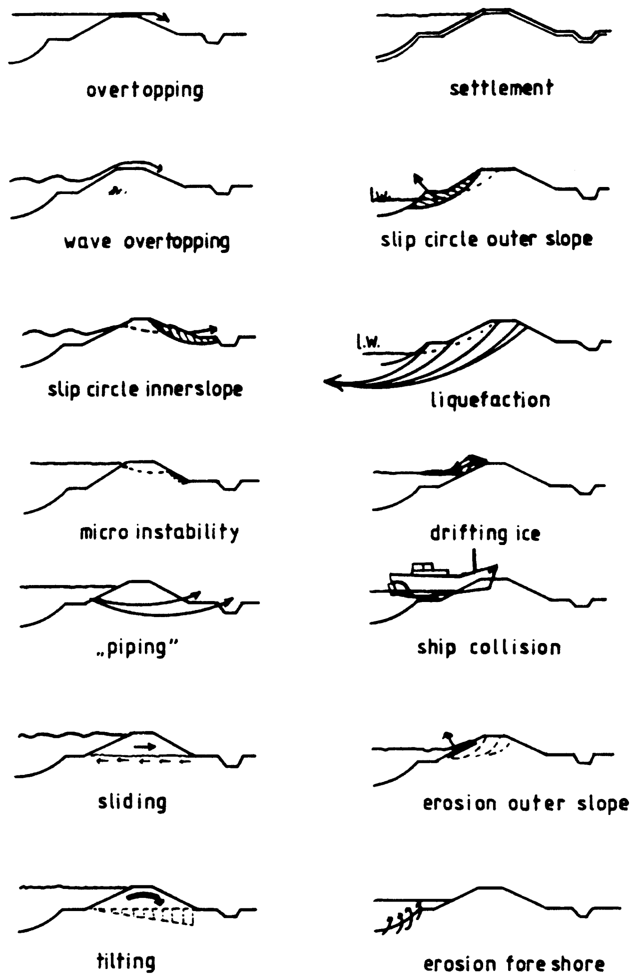

Fig. 2. Failure modes of a dike.

length of the dike ring has a considerable influence. A chain is as strong as the weakest link. So a single weak spot determines the actual safety of the dike ring.

The probabilistic approach aims to determine the probability of flooding of a polder and to judge its acceptability in view of the consequences. As a start the entire water defense system of the polder is studied. Typically this system contains sea dikes, dunes, river levees, sluices, pumping stations, high hills, etc. (Fig. 3).

In principle, the failure and breach of any of these elements leads to flooding of the polder. Thus, the probability of flooding results from the probabilities of failure of all these elements. Within a longer element e.g. a dike of 2 km length, several independent sections can be discerned. Each section may fail due to various failure mechanisms like overtopping, sliding, piping, erosion of the protected outer slope, ship collision, bursting pipeline, etc. The relation between the failure mechanisms in a section and the unwanted consequence flooding can be depicted with a fault tree as shown in Fig. 4 in which the following notation is used: R_i the resistance of section i, S the solicitation, h the height of the dike, B the width of the dike, wl the water levels in front of the dike, Hs the wave heights in front of the dike, and D the block diameter.

The failure probabilities of the mechanisms are calculated using the methods of the modern reliability theory like Level III Monte Carlo, Bayesian updating, Level II advanced first order second moment calculations (see Ref. [16] for a complete overview). The possibility to treat the human failure to close for instance a sluice in conjunction with structural failure is seen as a considerable advantage of the probabilistic approach (see Fig. 5). Nowak and Collins [9] devoted attention to this issue.

Correlations between failure modes and correlations between different dike sections have to be taken into account. Techniques are described, for instance in Ref. [4]. In the reliability calculations, all uncertainties should be dealt with. Three classes are discerned. The intrinsic uncertainty is characteristic for natural phenomena. Storm surge levels and extreme river discharges are intrinsically uncertain. Also, the uncertainty of the properties of the subsoil and of construction materials falls in this class. Model uncertainty describes the imperfection of the engineering

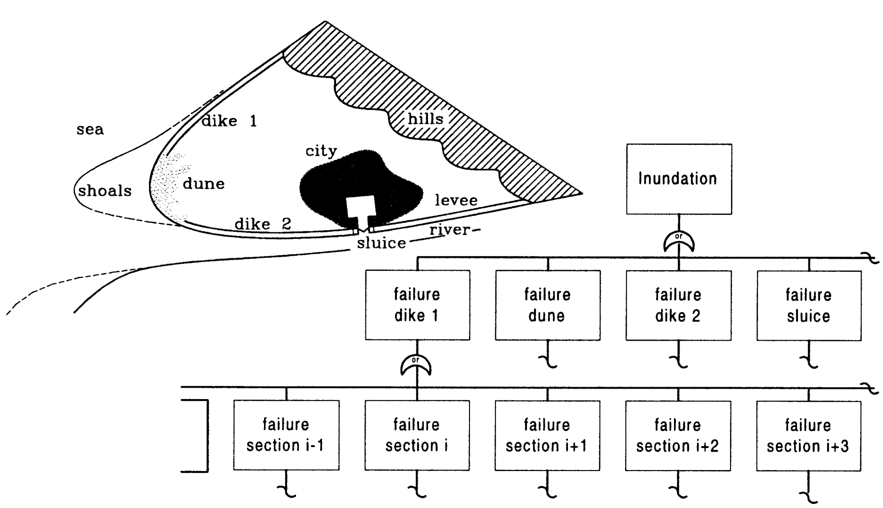

Fig. 3. Flood defense system and its elements presented in a fault tree.

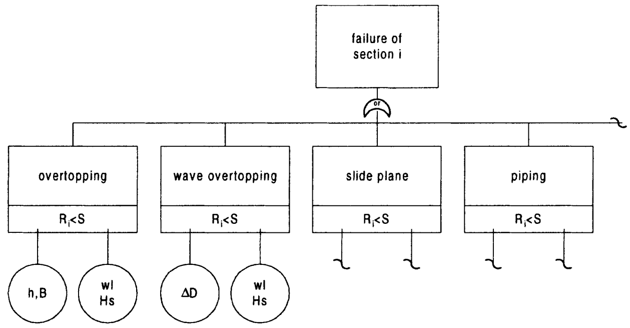

Fig. 4. A dike section as a series system of failure modes.

Table 1
Calculation table for the overall probability of flooding

Section	Overtopping	Piping	Etc.	Total
Dike section 1.1	$p_{1.1}$(overtop.)	$p_{1.1}$(piping)	$p_{1.1}$(etc.)	$p_{1.1}$(all)
Dike section 1.2	$p_{1.2}$(overtop.)	$p_{1.2}$(piping)	$p_{1.2}$(etc.)	$p_{1.2}$(all)
Etc.	⋮	⋮	⋮	⋮
Dune	p_{dune}(overtop.)	p_{dune}(piping)	p_{dune}(etc.)	p_{dune}(all)
Sluice	p_{sluice}(overtop.)	p_{sluice}(piping)	p_{sluice}(etc.)	p_{sluice}(all)
Total	p_{all}(overtop.)	p_{all}(piping)	p_{all}(etc.)	p_{all}(all)

models in predicting the behaviour of river courses, dikes and structures. The comparison of predictions and observations provides an estimate of this uncertainty. If such data lack, engineering judgement is the only feasible replacement. Statistical uncertainty is caused by the lack of data. These data are used to estimate the parameters of the probability distributions depicting the intrinsic uncertainty. Due to the paucity of data, the estimated values of the parameters are statistically uncertain. Because all uncertainties are included in the calculations of the failure probability, the latter is not singly a property of the physical reality but also of the human knowledge of the system [1,11].

The consequence is that the safety of the dike system as expressed by the calculated probability of flooding can be improved by strengthening the weakest dike but also by increasing our knowledge. The result of the calculated probability of flooding of the polder is presented in Table 1.

The last column of the table shows immediately which element or section has the largest contribution to the probability of flooding of the polder under study. Inspection of the related row reveals which mechanism will most likely be the cause. Thus, a sequence of measures can be defined which at first will quickly improve the probability of flooding but later runs into diminishing returns.

As stated earlier, the approach is tested on four polders of which the most important is shown here as an example. For Central Holland the 48 weakest dike sections, four dune sections and six structures were selected. The analysis showed that the probability of human failure to close a sluice structure at Katwijk dominated the system with a probability of 1/600 year. If it is assumed that this problem is solved in some way, then the probability of flooding becomes 1/2000 year. Piping under a dike near the village of Moordrecht determines this. If this piping problem can be solved, the probability of flooding sinks to 1/30,000 year. Now the dune along the North Sea near the village of Monster forms the weakest link. Improving the strength of this dune seems to reduce the flooding probability to 1/75,000 year. Although the example shows the results and the approach clearly, the last result is questionable as it hinges on the selection of the 48 + 4 + 6 elements at the start. Weaker links may yet be detected at this level.

Apart from a probabilistic approach of flooding, a probabilistic approach for maintenance schemes of deteriorating water defenses receives quite some attention lately. Maintenance planning can be based on reliability and risk

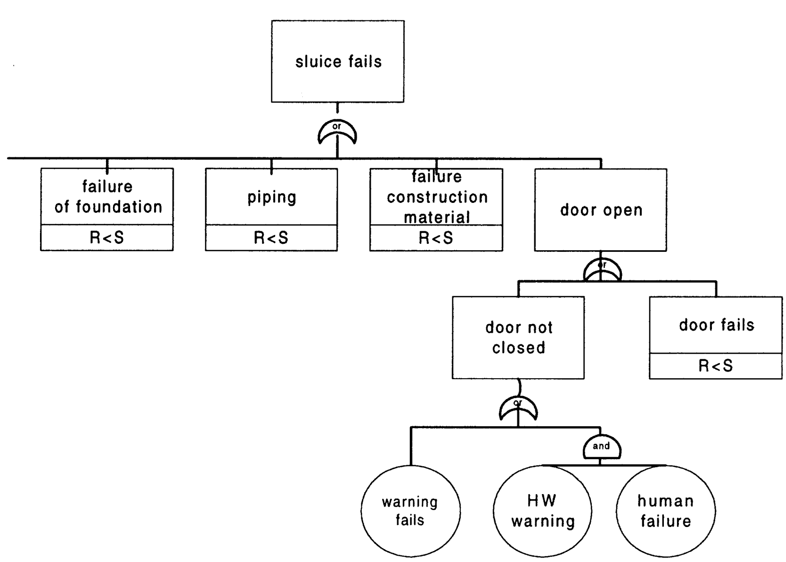

Fig. 5. The sluice as a series system of failure modes.

considerations, which include the degradation, the results of inspection and repair and the associated costs. Guedes Soares [2] gives an extensive overview, followed by a review of Vrijling [18].

4. The consequences of flooding

One of the tasks of human civilisations is to protect individual members and groups against natural and man-made hazards to a certain extent. The extent of the protection was in historic cases mostly decided after the occurrence of the hazard had shown the consequences. The modern probabilistic approach aims to give protection when the risks are felt to be high. Risk is defined as the probability of the disaster, i.e. a flood related to the consequences. As long as the modern approach is not firmly embedded in society, the idea of acceptable risk may, just as in the old days, be quite suddenly influenced by a single spectacular accident or incident like the non-calamitous threats of the Dutch river floods of 1993 and 1995.

The estimation of the consequences of a flood constitutes a central element in the modern approach. Most probably, society will look to the *total* damage caused by the occurrence of a flood. This comprises a number of casualties, material and economic damage as well as the loss of or harm to immaterial values like works of art and amenity. Even the loss of trust in the water defense system is a serious, but difficult to gauge effect. However, for practical reasons the notion of risk in a societal context is often reduced to the total number of casualties using a definition as: "the relation between frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards". If the specified level of harm is limited to loss of life, the societal risk may be modelled by the frequency of exceedance curve of the number of deaths, also called the FN-curve. The consequence part of a risk can also be limited to the material damage expressed in monetary terms as the Delta Committee did. It should be noted, however, that the reduction of the consequences of an accident to the number of casualties or the economic damage might not adequately model the public's perception of the potential loss. The schematisation clarifies the reasoning at the cost of accuracy.

The consequences in case of the flooding of polders will be estimated from two points of view. First, an estimate of the probability to die for an individual residing at some place in the polder will be given. The most practical form of presentation might be a contour plot of the risk as a function of the place in the polder. Secondly, the total number of people that will drown in a flood must be estimated. Because a polder can flood due to breaches at various places and according to different scenarios a FN-curve may be the best way to present this type of risk. Thirdly, the total material damage that will be caused by a flood must be estimated. For reasons mentioned above, a FN-curve may also be the best way to present this type of risk. It should be noted that the Delta Committee limited itself to the expected value of the material damage. The loss of life and the material damage will be estimated using cause–effect functions based on the experiences of the 1953 disaster. This could be criticised as considerable technical progress has been made providing people with better means but making society more vulnerable. Both increased as well as reduced effects can be deduced so that the cause–effect functions have stayed unaltered for the moment. As an example the FN-curve of the Brielse polder is shown in Fig. 6.

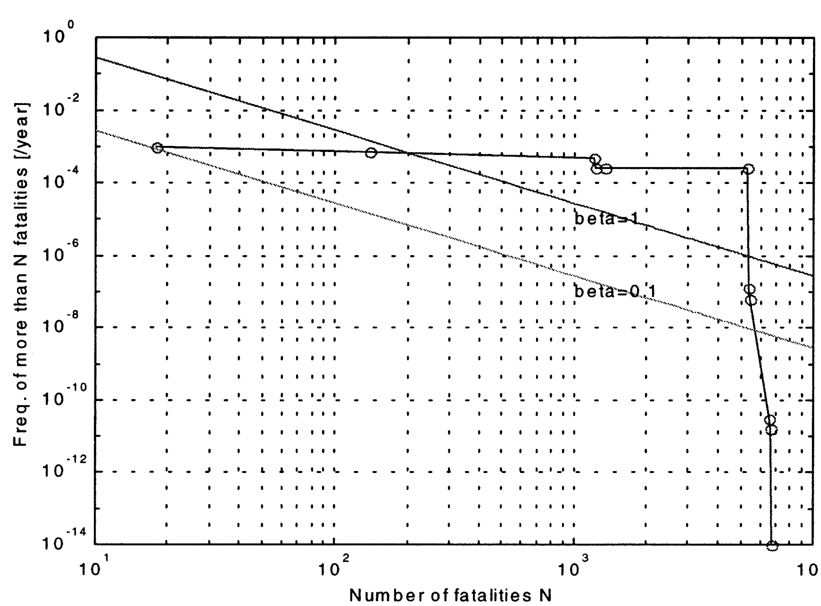

Fig. 6. FN-curve for flooding of the Brielse polder.

5. The decision problem or the notion of acceptable risk

Vlek and Stallen [17] investigated the judgments of risks for individual, societal and industrial activities. When the probabilities of flooding of the polders of the Netherlands are calculated the question will be: Are they safe enough? The answer to this question [12] should come from a broad judgement of the cost of improving the defenses against the reduction of the probability of flooding related to the scale of the damage. This judgement is political in essence, because the costs as well as the benefits contain many aspects that may be valued quite differently by different parties. Dike improvement costs money, cultural heritage and amenity. The valuation problem of the consequences was already discussed. However, the general picture is clear. If dike improvement is very expensive, a higher probability of flooding will be accepted. On the other hand, if the consequence of flooding is very substantial, one will aim for a smaller probability. As shown already in the example of the previous paragraph, an increasing effort will lead to an improvement of the safety of the dike that diminishes in the end. Efforts made to increase the knowledge as well as efforts to make structural improvements to the dike itself can be effective. Inspection of the existing dike system improves the knowledge and reduces the uncertainty. Checking the actual state of structural elements like sluices, pumping stations, etc. may be particularly effective. Further research may reduce the model uncertainty with respect to certain failure modes and some less well-known parameters. In the third place comes the classical improvement by increasing the height or the width of dikes. In principle, this involves much larger sums of money. Very effectively starting with the weakest sections one will quickly meet diminishing returns. Progressing with increasing cost means finally the upgrading of the dike ring to a higher standard. The reduction of the loading in the sense of water levels or wave heights is sometimes a fourth possibility. Widening the flood plain of a river to reduce the water level is a modern example. The reduction of the future consequences of flooding by adequate spatial planning or disaster management is the last and completely new avenue opened by the new approach. In order to make a choice the costs of the measures depicted above must be weighed against the reduction of the probability of flooding and the related consequences. It should be noted that the economic activity in the protected areas has grown considerably since the 1960s when the Delta Committee wrote its advice. Even more ambitious private and public investments, particularly in infrastructure, are planned. The national economy has therefore a far greater and still growing value exposed to flooding. Moreover, the safety of a growing number of inhabitants is at stake. Contrary to the old days, many people are presently housed in suburbs located in the deepest areas of the polders. In future, the environmental consequences of flooding and the potential effects on nature and cultural heritage will play an increasing role in assessing the required scale of flood protection. The image of The Netherlands, as a safe country to live, work, and invest, is finally at stake. This justifies a fundamental reassessment of the acceptability of the flood risks in view of the costs of improvement.

The smallest component of the social acceptance of risk is the assessment by the individual. Attempts to model this are not feasible; therefore it is proposed to look to the preferences revealed in the accident statistics. The fact that the actual personal risk levels connected to various activities show statistical stability over the years and are approximately equal for the western countries indicates a consistent pattern of preferences. The probability of losing one's life in normal daily activities such as driving a car or working in a factory appears to be one or two orders of magnitude lower than the overall probability of dying. Only a purely voluntary activity such as mountaineering entails a higher risk (Fig. 7).

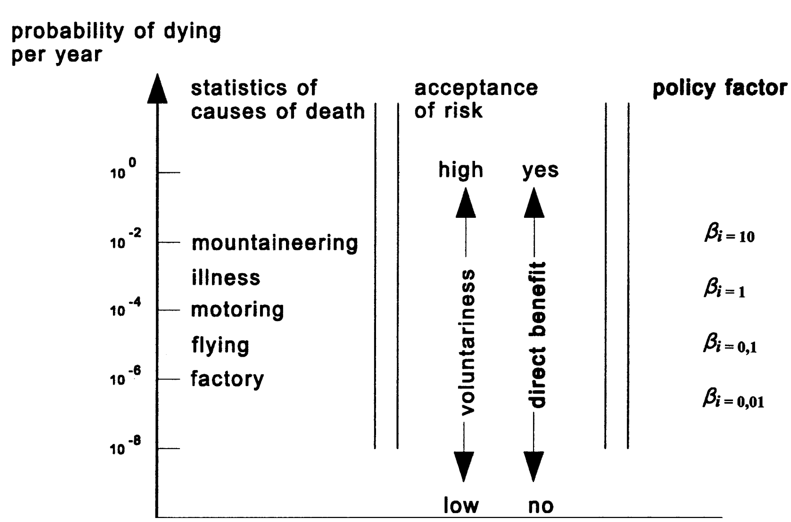

Fig. 7. Personal risks in western countries, deduced from the statistics of causes of death and the number of participants per activity.

Apart from a slightly downward trend due to technical progress, of the death risks presented, it seems permissible to use them as a basis for decisions with regard to the personally acceptable probability of failure in the following way:

$$P_{fi} = \frac{\beta_i \times 10^{-4}}{P_{d|fi}}$$

where $P_d|_{fi}$ denotes the probability of being killed in the event of an accident. In this expression, the policy factor β_i varies with the degree of voluntariness with which an activity i is undertaken and with the benefit perceived. It ranges from 100 in the case of complete freedom of choice like mountaineering, to 0.001 in case of an imposed risk without any perceived direct benefit [10]. This last case includes the individual risk criterion used for the siting of a hazardous installation near a housing area without any direct benefit to the inhabitants. A proposal for the choice of the value of the policy factor β_i as a function of voluntariness and benefit is given in Table 2.

For the safety of dikes, a β_i-value of 1.0–0.1 is thought to be applicable. The judgement of societal risk due to a certain activity should be made on a national level. The risk on a national level is the aggregate of the risks of local installations or activities. Starting with a risk criterion on a national level one should evaluate the acceptable local risk level, in view of the actual number of installations, the cost/benefit aspects of the activity and the general progress in safety, in an iterative process with say a fifty year cycle.

The determination of the socially acceptable level of risk assumes also that the accident statistics reflect the result of a social process of risk appraisal and that a standard can be derived from them. The formula should account for risk aversion in a society. Relatively frequent small accidents are more easily accepted than one single rare accident with large consequences like a flood, although the expected number of casualties is equal for both cases. The standard deviation of the number of casualties reflects this difference.

As shown by Vrijling et al. [21], risk aversion can be represented mathematically by adding the desired multiple k of the standard deviation to the mathematical expectation of the total number of deaths, $E(N_{di})$ before the situation is tested against the norm of β_i. 100 casualties for the Netherlands:

$$E(N_{di}) + k\sigma(N_{di}) < \beta_i \times 100$$

where $k = 3$ risk aversion index.

To determine the mathematical expectation and the standard deviation of the total number of deaths occurring annually in the context of activity i, it is necessary to take into account the number of independent places N_{Ai} where the activity under consideration is carried out.

The translation of the nationally acceptable level of risk to a risk criterion for one single installation or polder where an activity takes place depends on the distribution type of the number of casualties for accidents of the activity under consideration. In order to relate the new local risk criterion to the FN-curve, the following type is preferred:

$$1 - F_{N_{dij}}(x) < \frac{C_i}{x^2} \qquad \text{for all } x \geq 10$$

If the expected value of the number of deaths is much smaller than its standard deviation, which is often true for the rare calamities studied here, the value of C_i reduces to:

$$C_i = \left[\frac{\beta_i \times 100}{k\sqrt{N_{Ai}}} \right]^2$$

The problem of the acceptable level of risk can be also formulated as an economic decision problem as explained earlier. The expenditure I for a safer system is equated with the gain made by the decreasing present value of the risk (Fig. 1). The optimal level of safety indicated by P_f corresponds to the point of minimal cost.

$$\min(Q) = \min(I(P_f) + \mathrm{PV}(P_f S))$$

where Q is the total cost, PV, the present value operator and S is the total damage in case of failure.

If despite ethical objections, the value of a human life is rated at s, the amount of damage is increased to:

$$P_{d|fi} N_{pi} s + S$$

where N_{pi} is the number of inhabitants in polder i.

This extension makes the optimal failure probability a decreasing function of the expected number of deaths. The valuation of human life is chosen as the present value of the net national product per inhabitant. The advantage of taking the possible loss of lives into account in economic terms is that the safety measures are affordable in the context of the national income [19].

In assessing the required safety of a dike system the three approaches described above should all be investigated and presented. The most stringent of the three criteria should be adopted as a basis for the 'technical' advice to the political decision process. However, all information of the risk assessment should be available in the political process.

Table 2
The value of the policy factor β_i as a function of voluntariness and benefit

β_i	Voluntariness	Benefit	Example
100	Voluntary	Direct benefit	Mountaineering
10	Voluntary	Direct benefit	Motor biking
1.0	Neutral	Direct benefit	Car driving
0.1	Involuntary	Some benefit	Factory
0.01	Involuntary	No benefit	LPG-station

6. Conclusions

The new probabilistic approach has great advantages compared with the present. The event that the system of water defenses is meant to prevent (flooding) comes at the centre of the analysis. The contribution of all elements of the system and of all failure, mechanisms of each element to the probability of flooding is calculated and clearly presented. The possibility to include the probability of human failure in the management of water defense structures is especially attractive and useful. The length effect, meaning that a longer chain is likely to have a weaker link, can be adequately accounted for.

The results of the application of the method to Central-Holland reveal indeed a ranking of the weaker elements. A plan to invest increasing amounts of money by progressively improving the elements can be defined on the basis of the analysis. At this moment the optimal inspection and maintenance of the dike system amalgamates into a farsighted plan to improve the safety of the entire system. Also a wider scale of measures becomes eligible for decision making with the new method than before. Investments in inspection, in research and in adapting spatial plans are alternatives that can be compared with the classical measures of dike improvement.

Finally, an approach is sketched to define the level of acceptable risk. The decision on the level of acceptable risk is a cost/benefit judgement that must be made from individual as well as from societal point of view. A system of three rules is developed to support the decision how safe the dikes should be. The most stringent of the three criteria should be adopted as a basis for the 'technical' advice to the political decision process. However, all information of the risk assessment should be available in the political process. A decision that is political in nature must be made democratically, because many differing values have to be weighted. The economic optimisation may however show that the economic activity in the protected areas has grown so much since the 1950s that a fundamental reassessment of the acceptability of the flood risks is justified. Moreover, the image of the Netherlands as a safe country to live, work, and invest in is an important factor to consider especially whenever more ambitious private and public investments, particularly in infrastructure, are planned.

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